

Development of a W-band Serpentine Waveguide Amplifier based on a UV-LIGA Microfabricated Copper Circuit

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Abstract: We are developing a 95 GHz, 200 W, wideband vacuum electronic amplifier based on a 20 kV, 120 mA electron beam. The serpentine circuit is fabricated by multi-layer UV-LIGA using an embedded polymer monofilament, which produces an all-copper monolithic structure with beam tunnel. We also discuss extension of the technique to upper millimeter-wave circuits at 670 GHz.

Keywords: UV-LIGA; vacuum electron devices

Introduction

Vacuum electron devices operating in the spectral range from 100 GHz to 1 THz require millimeter wave circuits with feature sizes in the range 10-100 μm . An ultraviolet photolithography process, combined with copper electroforming (UV-LIGA), is being developed at the U.S. Naval Research Laboratory to span this range. A Patent-pending technique produces monolithic all-copper circuits, integrated with electron beam tunnel, suitable for high-power continuous-wave operation [1]. We have demonstrated circuits complete with beam tunnels at 220 GHz [2] and 670 GHz to date. In this paper, we discuss UV-LIGA microfabrication of a 95 GHz serpentine waveguide circuit for a wideband, 200 W W-band traveling-wave tube amplifier. We also present recent progress on microfabrication of 670 GHz circuits.

Millimeter wave (mmW) amplifiers in the W-band (75-110 GHz) frequency range producing >100 W over several GHz of instantaneous bandwidth are needed for high-resolution radar and high-data-rate communications. These amplifiers require robust all-copper interaction circuits to withstand the extreme temperatures of continuous high-power operation, which is a limitation in the mmW regime for the helix-type circuit typically used in wideband traveling-wave tubes [3]. The serpentine waveguide (SWG) circuit, in which a TE10 rectangular waveguide mode travels through a series of smooth 180-degree bends while exchanging energy with an electron beam, is an alternative to the helix that is amenable to planar microfabrication. The SWG is a good balance between the wide bandwidth of a helix and the high output power of a coupled-cavity type circuit [4]. Recently developed microfabrication techniques for mmW and terahertz range structures will be used to create all-copper, monolithic SWG circuits with beam tunnel [5,6] for a high-power, wideband W-band traveling-wave tube (TWT) amplifier.

UV-LIGA is also a promising technique at higher frequencies, in the sub-mmW and THz regime. At these frequencies, circuit features are too small to be made with state-of-the-art conventional machining, but too deep ($> 100 \mu\text{m}$) to be compatible with typical lithographic techniques. The ability of the SU-8 photoresist to form a deep coating (up to 1 mm) and to layer enables the fabrication of solid copper circuits deeper than 1 mm with 10:1 aspect ratio to ~ 5 micron precision.

W-Band Amplifier Design

The serpentine waveguide amplifier is designed to be powered by a 20 kV, 122 mA electron beam, electrostatically focused to a diameter of $< 200 \mu\text{m}$ and guided by a 0.6 T permanent magnet solenoid. The formation and transport of a high-current-density electron beam is critical to the wide-band, high-power operation of the amplifier [7, 8]. The interaction circuit consists of two traveling-wave stages separated by a power-dissipating sever, to increase the gain while avoiding spurious oscillation. 3D particle-in-cell (PIC) physics simulations are used to predict the amplifier performance. The small-signal gain is approximately 37 dB. The predicted peak output power is 245 W, with > 200 W of power over a 4 GHz bandwidth and > 100 W over a 7 GHz bandwidth. The electronic efficiency at maximum output power is 10%. Figure 1 shows the predicted saturated

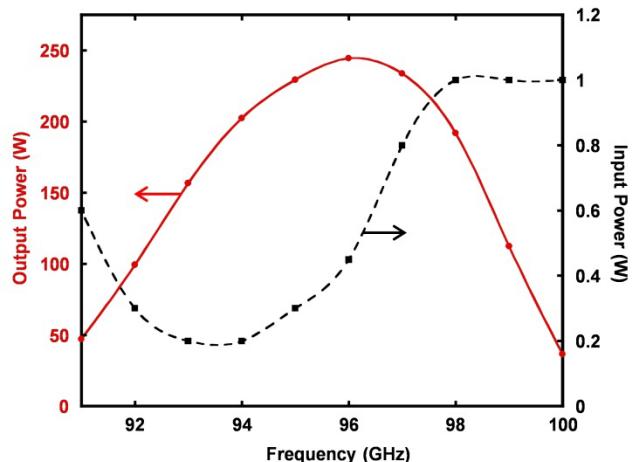


Figure 1. Simulated saturated output power (left axis) over 91-100 GHz, with input power (right axis) limited to 1 W.

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Table 1. W-band amplifier operating parameters.

| | |
|-------------------|----------------|
| Beam voltage | 20 kV |
| Beam current | 122 mA |
| Small signal gain | 37 dB |
| 3-dB Bandwidth | 5 GHz, nominal |
| Frequency range | 91-100 GHz |
| Max output power | 245 W |
| Efficiency | 10% |

output power in the 91-100 GHz range, with the input power limited to 1 W to ensure compatibility with a solid-state drive source. The amplifier operating parameters are shown in Table 1.

W-Band Circuit Fabrication

A multi-layer UV-LIGA embedded monofilament technique is used to create the high vertical aspect ratio serpentine features required for the circuit, simultaneously with the electron beam tunnel [5,6]. Three layers of alternating SU-8 deposition and electroforming will be used to build up the complete copper circuit to the 1700 μm final thickness. A polymer monofilament will be embedded in the center layer to form the 230 μm diameter beam tunnel. The UV-LIGA procedure is diagrammed in Figure 2. A hardened layer of SU-8 photoresist is deposited on a copper substrate, and exposed to UV light through a lithographic mask defining the circuit geometry. The exposed SU-8 is developed chemically to create a negative-relief mold, and copper is electroformed over the SU-8 to create the circuit. The copper circuit with SU-8 inside is planarized by grinding/polishing to the desired thickness of the first layer (Fig 2a). A polymer monofilament is fixed in place above the first layer, held at the desired position of the beam tunnel by guide pieces (Fig. 2b). The filament material is ethylene tetrafluoroethylene (ETFE), chosen because its UV refractive index is close to SU-8, and because its thermal and tensile strength are suitable to withstand the process [5]. A second lithographic SU-8/copper layer is formed around the filament (Fig. 2c). The second layer is planarized, and the third layer is created on top (Fig. 2d). When the final circuit depth is achieved, the SU-8 and monofilament are removed to leave the 3D copper structure. A copper plate cover is brazed on top to complete the circuit.

An important parameter for the ultimate performance of the circuit is the geometry of the waveguide cross section. The waveguide depth is 1700 μm and the width (the length of the beam-wave interaction gap) is 252 μm , for an aspect ratio of ~7:1. It is difficult to achieve low sidewall angles on a SU-8 layer thicker than ~600 μm using a UV exposure wavelength of 365 nm, due to non-uniform UV absorption from the top to the bottom of the layer [6]. Figure 3 shows photographs and measurements of the first layer of SU-8 on the mirror-finish copper substrate, after UV exposure/developing and prior to electroforming. Measurements of the side profile, taken by cleaving the

SU-8 and viewing the cross section, indicate a low sidewall angle of ~0.7° (Fig. 3c).

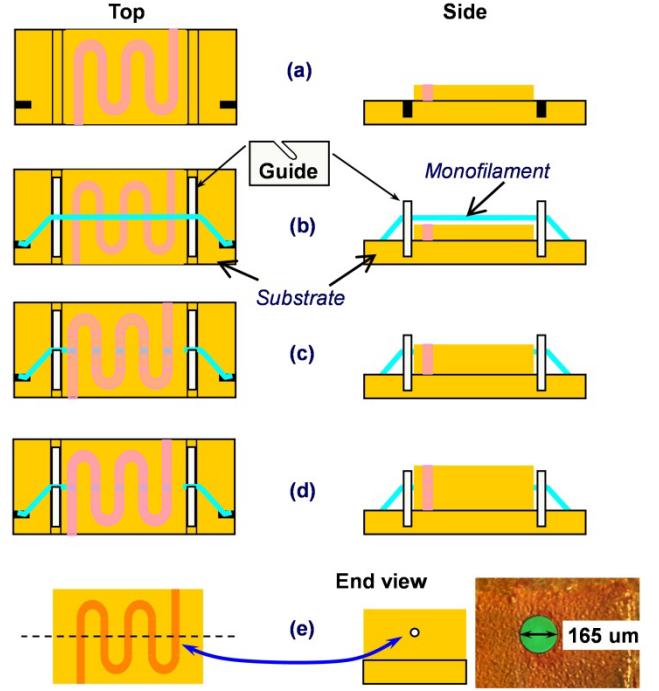


Figure 2. Embedded polymer monofilament multi-layer UV-LIGA method. (a) The first layer of the circuit is electroformed and planarized with SU-8 remaining, (b) the monofilament is fixed in place above the copper, (c) the second layer is electroformed and planarized with SU-8 and filament remaining, (d) the final layer is electroformed and planarized, (e) the SU-8 and monofilament are removed. A side view photo of an example final circuit with backlit 165 micron diameter beam tunnel is shown.

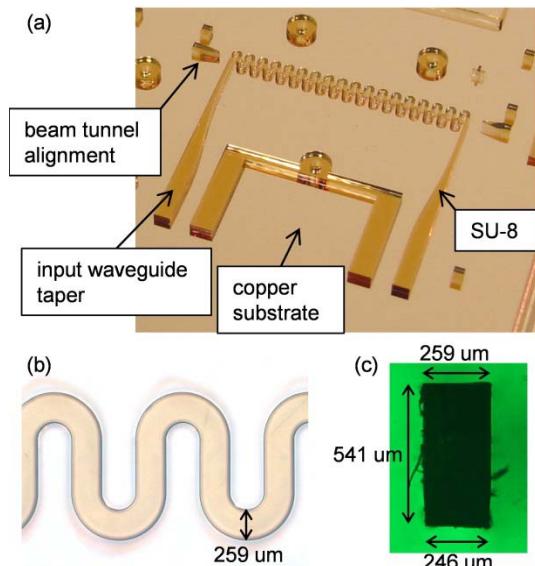


Figure 3. UV-LIGA microfabrication. (a) SU-8 circuit forms of first layer on mirror-finish copper substrate, prior to electroforming. (b) Optical micrograph of SU-8 serpentine waveguide form. (c) Silhouette of SU-8 waveguide cross section, showing side wall angle < 1°.

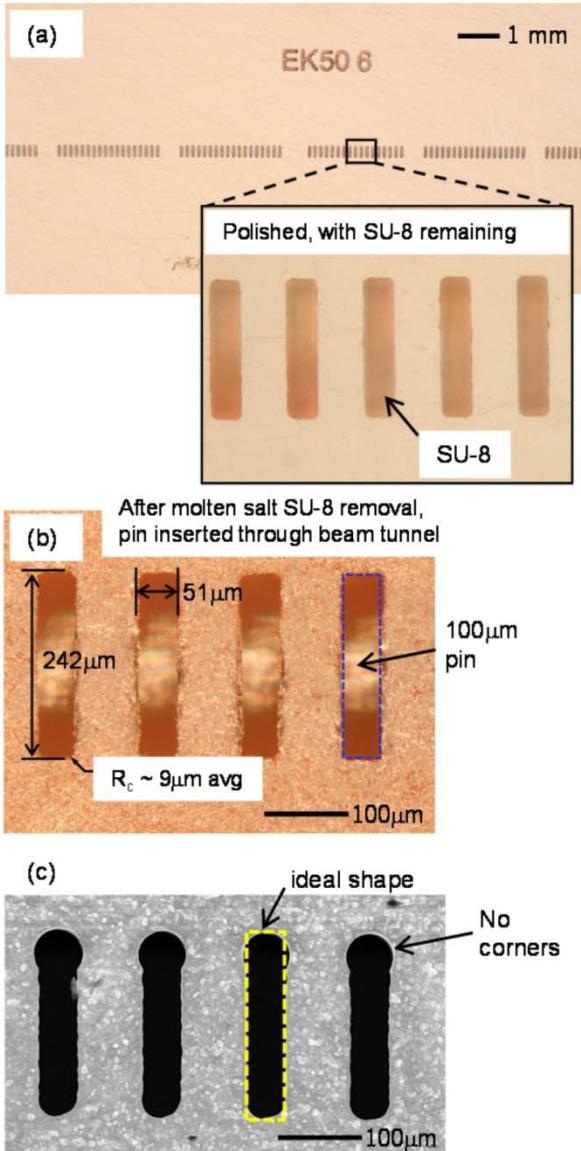


Figure 4. Single-layer fabrication of 670 GHz ladder circuit for an extended interaction klystron. (a) Top view of circuit after copper electroforming and polishing, with SU-8 remaining. (b) Circuit after removal of SU-8 by molten salt. A 100 micron diameter steel pin can be seen (out of focus) passing through the beam tunnel. (c) Circuit fabricated by wire EDM at industry machine shop.

670 GHz Circuit Fabrication

In order to demonstrate the suitability of UV-LIGA for THz-range devices, we fabricated a 670 GHz ladder-style copper circuit similar to that used in an extended interaction klystron amplifier [9]. The circuit consists of a series of groups of 18 rectangular slot cavities 280 μm deep, connected by a beam tunnel 100 μm in diameter. The aspect ratio of the slots is 5.5. The circuit was fabricated in a single lithographic step, as opposed to the multi-layer process described in the previous section.

Fig. 4a shows a top view of the circuit after copper electroforming and polishing, with SU-8 remaining in place. The beam tunnel monofilament runs inside the copper horizontally through each group of slots seen in the figure. Fig. 4b shows a close-up of a group of slots after removal of the SU-8 by molten salt, along with dimensions measured using an optical inspection microscope. A steel pin 100 μm in diameter is seen inserted through the beam tunnel. The corner radius of the slots, which ideally would be perfect rectangles, is 9 μm on average. This result is compared with the same circuit fabricated by wire electrical discharge machining (EDM) at an industry machine shop (Fig. 4c). The slots are circular at the ends, with no corners visible. This is due to the cutting wire size and pilot hole limitations of the wire EDM technique.

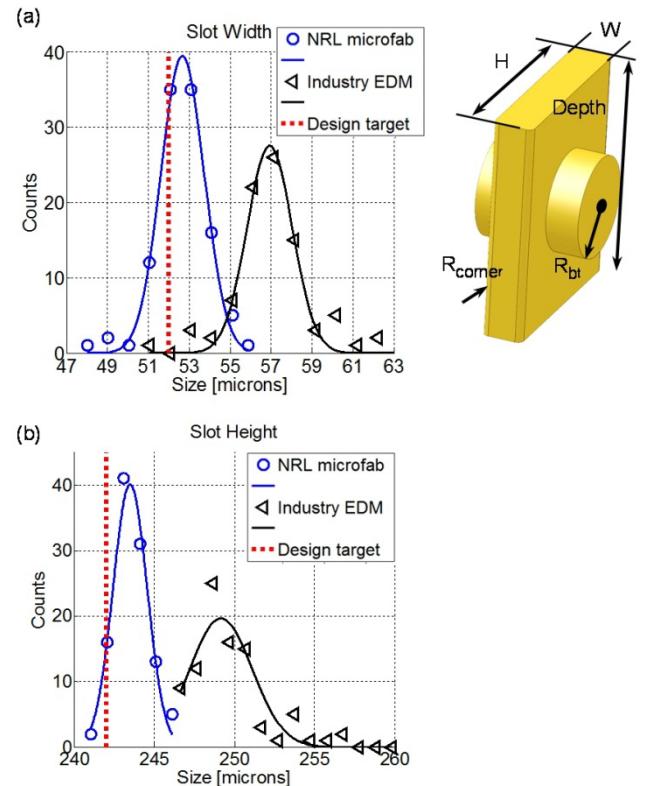


Figure 5. (a) Histograms of slot width W and (b) slot height H measurements of 670 GHz UV-LIGA fabricated circuits (circles), compared to a circuit fabricated by wire EDM (triangles). Solid lines are Gaussian fits to the data. The red vertical dashed line indicates the design target dimensions.

Fig. 5 shows histograms generated by measuring each slot width and height in both circuits. The accuracy and precision (spread) of the achieved dimensions across all slots is measured by Gaussian curve fits to the data. It is seen that the UV-LIGA microfabricated circuit is more precise, with a smaller spread in measured dimensions, and is closer to the design target (vertical dashed red line) in both the slot width (Fig. 5a) and height (Fig. 5b). The standard deviations of all measured dimensions are listed

in Table 2. The standard deviation of measured values of the UV-LIGA circuit across all slots is approximately 1 um, half that of the EDM circuit, and the standard deviations of dimensions of the best group of 18 slots (see Fig. 4a) is significantly better (Table 2, “NRL best” column).

Table 2. 670 GHz circuit measurement statistics.

| Std. Dev. (um) | NRL best | NRL all | EDM all |
|-------------------------------|----------|---------|------------|
| Width, W | 0.71 um | 1.29 | 2.2 |
| Height, H | 0.72 | 1.08 | 2.14 |
| Period, P | 0.62 | 0.99 | 2.14 |
| Depth, D | 0.41 | 1.83 | n/a |
| Corner radius, R _c | 0.92 | 1.33 | No corners |

Summary

A novel UV photolithography copper electroforming process (UV-LIGA), developed at the U.S. Naval Research Laboratory, is being used to create monolithic all-copper millimeter wave amplifier circuits complete with electron beam tunnels for use in the 100-1000 GHz frequency range. The technique enables accurate and highly repeatable fabrication of robust copper circuits, capable of withstanding high-power continuous-wave operation, for sub-millimeter and terahertz range vacuum electron devices. We have demonstrated circuits at 220 and 670 GHz to date. Work is currently in progress to demonstrate a wide-band, 200 W, 95 GHz traveling-wave tube amplifier based on a UV-LIGA circuit.

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